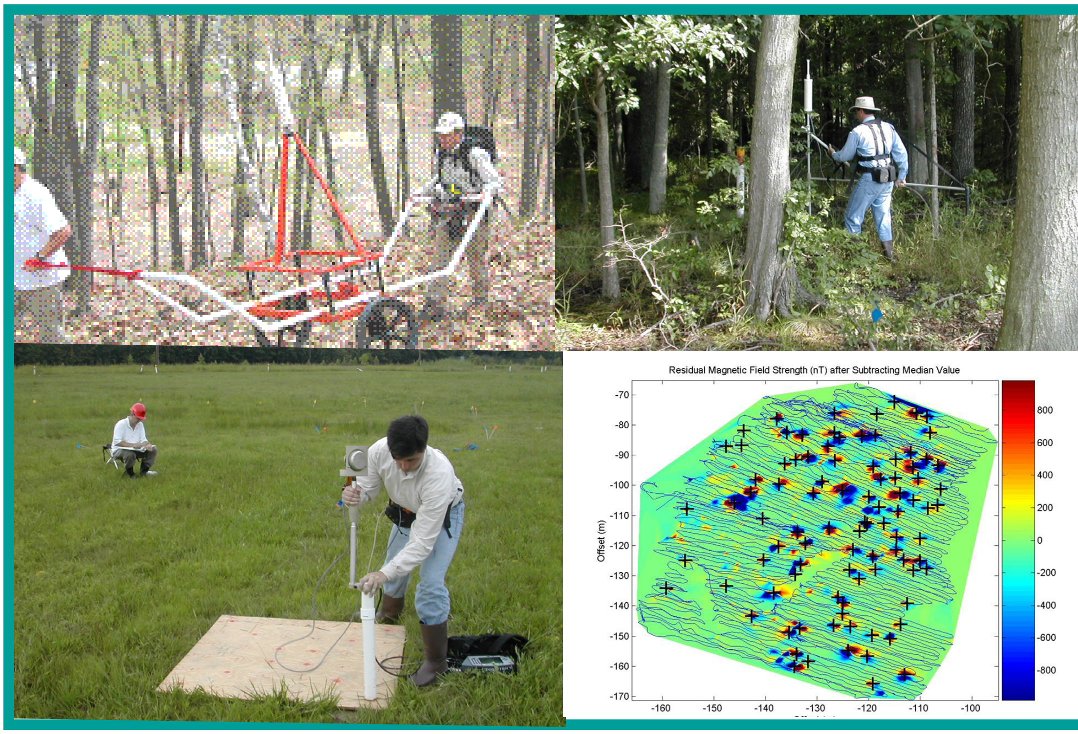
ESTCP
Cost and Performance Report

(MM-0029)



UXO Precise Position Tracking Ranger

January 2008

ENVIRONMENTAL SECURITY
TECHNOLOGY CERTIFICATION PROGRAM

U.S. Department of Defense

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COST & PERFORMANCE REPORT
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ACRONYMS AND ABBREVIATIONS

APG	Aberdeen Proving Grounds
cm	centimeter
DGM	digital geophysical mapping
DGPS	differential global positioning system
DoD	Department of Defense
DSSS	direct sequence spread-spectrum
ESTCP	Environmental Security Technology Certification Program
FCC	Federal Communications Commission
ft	foot, feet
FUDS	formerly used defense sites
GFE	government-furnished equipment
GGA	Generalized Gradient Approximations
GHz	gigahertz
GPS	global positioning system
IMU	inertial measurement unit
ISM	industrial, scientific, and medical
kbps	kilobit(s) per second
LAN	local area network
m	meter, meters
ms	millisecond, milliseconds
NMEA	National Marine Electronics Association
OE	ordnance and explosives
PDA	personal digital assistant
PPS	pulse per second
RF	radio frequency
RTS	robotic total station
SOP	standard operating procedure
TTL	time to live

USACEHNC	U.S. Army Corps of Engineers–Huntsville Center
UXO	unexploded ordnance

ACKNOWLEDGEMENTS

This project would not have been possible without the combined financial support of the Environmental Security Technology Certification Program (ESTCP), the U.S. Army Corps of Engineers – Huntsville Center (USACEHNC), and ENSCO, Inc. Their continuing support is gratefully acknowledged. In addition, the staff at Aberdeen Proving Grounds (APG) provided excellent support facilitating the demonstration.

Technical material contained in this report has been approved for public release.

1.0 EXECUTIVE SUMMARY

ENSCO, Inc. has made a significant technological improvement in position and navigation methodology for unexploded ordinance (UXO) operations, especially in areas where conventional technologies are ineffective. In conjunction with funding from the ESTCP and the USACEHNC, ENSCO has conducted three navigation and geolocation demonstrations at McKinley Test Range/Redstone Arsenal, Huntsville, Alabama, and at the APG, Aberdeen, Maryland. These demonstrations were conducted between 2002 and 2004 for quantifying the navigation performance of ENSCO, Inc.'s Ranger radio frequency navigation system. Quantitative evaluation of the results of this demonstration has been conducted separately by USACEHNC.

1.1 BACKGROUND

UXO poses a threat to both human life and the environment. Millions of UXO may be located in the United States on active test and training ranges and on formerly used defense sites (FUDS). There may be as much as 30 million acres contaminated in more than 1,500 sites. Essentially all the project investigations involve the use of digital geophysical mapping (DGM) to detect and locate buried UXO. One of the major challenges with DGM is accurate navigation for sensor position. This is especially problematic in vegetation and under tree canopies. Accurate, inexpensive, and easy-to-use navigation systems with consistent quality are needed for surveys in all terrain and vegetation cover. Navigation accuracy is essential for effective DGM.

The demonstrated technology described will support geophysical mapping of FUDS, active Department of Defense (DoD) installations, defense sites identified under the Base Realignment and Closure (BRAC) Act, property adjoining DoD installations, and other federally controlled/owned sites that have been impacted by ordnance and explosives (OE) operations.

ENSCO has conducted three demonstrations of the Ranger radio frequency (RF) precise positioning and communication system—two at the McKinley Range, Redstone Arsenal, Alabama, in 2001 and 2003, and a final demonstration at Aberdeen Proving Grounds, Maryland, at the UXO Technology Demonstration Site in July 2004. In addition, Ranger was provided to a commercial DGM firm for use at a live site project at Fort Devens, Massachusetts, in June 2005.

1.2 OBJECTIVES OF THE DEMONSTRATIONS

The primary objective of the demonstrations was to determine the applicability of ENSCO's Ranger positioning technology to support in-the-woods navigation as well as terrain-obstructed geophysical mapping activities. These are applications where the differential global positioning system (DGPS) is ineffective or has greatly reduced accuracy.

Demonstrations consisted of navigation equipment fully integrated with a Geometrics 858 cesium vapor magnetometer or a Geonics EM-61 electromagnetic metal detector. The initial focus was on acquiring high accuracy, fixed point navigation and large area data mapping by integrated navigation and geophysical sensor equipment. Selected anomalies from a dig list were reacquired to verify ability and accuracy in reacquisition.

The system was evaluated on the navigation positions as recorded for the known and unknown surface control points and on dig list locations for unknown subsurface anomalies. Surface points were separately evaluated for acquired position from the navigation equipment, from sensor profiles, and by the selected position from the gridded geophysical data's anomaly representation.

1.3 REGULATORY DRIVERS

This project is primarily motivated by the requirement for more efficient and accurate OE field operations to achieve better technical remediation performance and to reduce cost. Precise navigation and positioning technology is an important part of the infrastructure of OE remediation efforts as an enabling tool to allow faster, better, and cheaper detection, characterization, and excavation. Regulatory issues do not affect the use of this technology.

1.4 DEMONSTRATION RESULTS

Demonstration results show that Ranger navigation technology:

- Is easy to set up and use with minimal training
- Is integrated with Geometrics G-858 magnetometer and Geonics EM-61 electromagnetic metal detector
- Provides ~20 cm positioning accuracy (1 σ) in minimally cluttered outdoor environments, ~50 cm positioning accuracy (1 σ) in heavily wooded terrain
- Has a range of operation >1 km in minimally cluttered outdoor environments, >120 m in heavily wooded terrain
- Is effective as an advance prototype but requires further modification for robust field use
- Is sensitive to the method used to locate fixed-location radios.

1.5 STAKEHOLDER/END-USER ISSUES

The demonstrated technology documented the accuracy of Ranger navigation technology integrated with industry standard geophysical sensors. Results of the demonstration provide end users an understanding of the technical, logistical, and financial impact and allow informed decision making by the end user for appropriate applications.

2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY DEVELOPMENT AND APPLICATION

Ranger, a wide-area radio navigation technology, was developed to serve navigational needs, primarily in areas where conventional global positioning system (GPS) is ineffective or insufficiently accurate. Ranger is suited for densely wooded environments where GPS, laser, and acoustic techniques fail.

The GPS system is a spread-spectrum distance measuring system, where the distance from a user to several satellites is measured. Knowing the positions of the satellites, it computes the position of the user. A local radio frequency (RF) positioning system operates similarly—distances from a user are measured to a suite of local RF transponders (instead of satellites), and the position is computed from these measured distances. Figure 1 shows the general concept of operations.

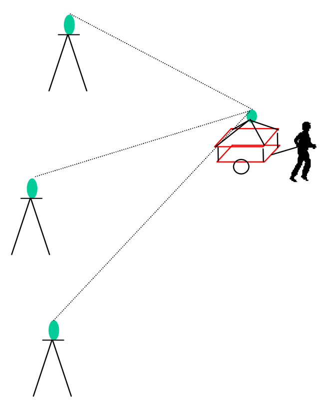

Figure 1. Concept of Operations

GPS measures the distance from the satellite to the user using one-way communications, generating the so-called pseudo-range, and the unknown clock time of the user is computed as part of the position calculation. In our local system, the actual distance is measured from the user to the fixed transceivers with a round-trip duplex communication scheme. Therefore, actual distances (ranges) are measured.

The fundamental aspect of this scheme is the one-dimensional distance measuring technique. The method relies on direct sequence spread-spectrum (DSSS) communications in the 2.4 GHz industrial, scientific, and medical (ISM) band (the same band used by spread-spectrum modems, 802.11(b,g) communications, Bluetooth™, and microwave ovens). Distance measuring techniques using spread-spectrum communications are well known in the literature (e.g., Intersil, 2000). However, these techniques are also well known to provide position uncertainties on the order of tens of meters, which is inadequate for DGM and UXO needs. The key to our approach is the method described in U.S. Patent Number 6,067,039, issued May 23, 2000, entitled "Systems and Methods for Determining the Distance Between Two Locations" (ENSCO holds the exclusive license for positioning technologies using this patent).

The inventors of this patent crafted a clever means to improve the accuracy of DSSS ranging. By exploiting small, intentional differences in the clock frequency between the user's DSSS radio (the mobile radio) and the fixed radios, there is a periodic slip in the DSSS signal that is a function of the difference in the two clock frequencies. By calibrating this slip, we acquire a fine resolution distance measuring capability to enhance the "coarse" resolution achievable by these previously well-known means.

The current implementation requires between 20 and 50 ms to measure the round-trip travel time between the mobile user and a fixed radio. While this measurement is taking place, the system can simultaneously communicate digital data between the mobile and fixed radios (because the distance measuring transmission can carry information.) The current system implements a 38.4 kbps wireless communications link.

For the most recent ESTCP demonstration, we have integrated Ranger with a Geometrics G-858 magnetic sensor system. A portable data logger acquires data both from the G-858 and Ranger and stores them for later analysis and display. Ranger's clock provides the time base for both position and magnetic data. Similar demonstrations were previously performed with Ranger integrated with a Geonics EM61-MKI. Also, Ranger has been integrated and tested with a Geonics EM61-MKII for a trial in commercial UXO remediation activities. This effort was achieved through unrelated funding.

In addition to storing data on the mobile data logger, we also exploit the wireless communications capability of Ranger to communicate the data off site to allow a supervisor or monitor to observe in real time the position of the mobile user and to see the acquired G-858 data. This real-time quality control and data analysis should significantly enhance field operations. The data is received and displayed using custom-developed software that passes the range data to a Kalman filter that computes the mobile radio's coordinates and generates a real-time track map. Figure 2 shows a schematic of the system. Four fixed units are shown although any number of fixed radios greater than two can be deployed, depending on the particular environment. Six to eight fixed units are typically used.

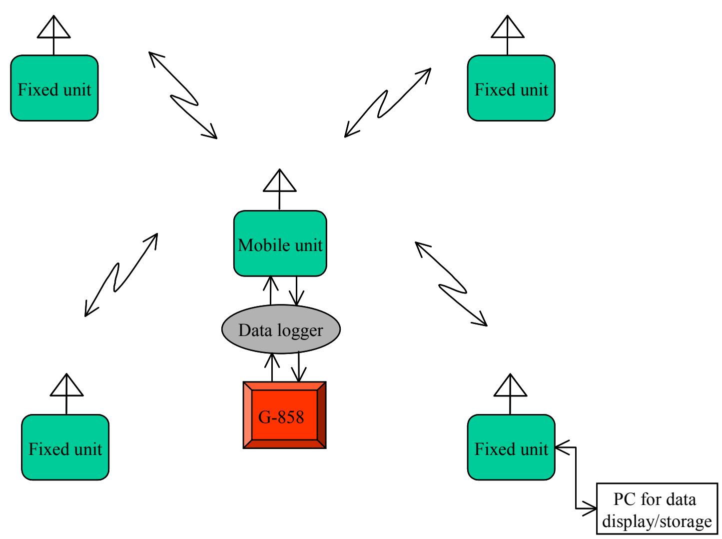

Figure 2. Schematic of Ranger Configuration

This DSSS distance measuring technology was originally developed for a golf course distance-to-the-pin commercial product. It was designed to achieve an accuracy of 1 m, the resolution needed to aid a golfer. Testing of the preproduction prototype showed this design goal was met. Because this is a commercial activity unrelated to the present project, test data from the original ranging product are not included.

In the summer of 2000, ENSCO conducted a study of this technology to assess whether the system could be redesigned to achieve greater accuracy and precision. That study indicated that, by making several straightforward modifications to the design (e.g., using more stable clocks in each radio), the accuracy should improve to at least 20 cm and possibly 10 cm.

Based on that study, ENSCO initiated development of a multidimensional ranging system for geophysical data acquisition. This development was not financed under the present project.

Further development of Ranger for UXO operations was funded by ESTCP under project MM-0029 and three phases of demonstrations were conducted in association with project MM-0129, at the McKinley Range of Redstone Arsenal and the Aberdeen Proving Grounds (APG). For the Phase III demonstration at APG, we made the following enhancements to the geopositioning software:

- Integrated the data acquisition software with a Geometrics G-858 magnetometer

- Migrated the Kalman filter that takes the input range measurements and produces geolocation data as output to the handheld computer (we use an iPaq) so that the sensor operator could see real-time position data, which is particularly useful for relocation

- Measured more accurate thermal calibration drift curves for the radios and incorporated them into the measurement process

- Simplified the user interface to the postprocessing software to allow a nonexpert user to operate it

In addition, we manufactured and delivered a complete system, hardware and software, to USACEHNC for further testing, evaluation, and use in select actual geophysical operations.

2.2 PROCESS DESCRIPTION

Mobilization and installation requires 20–30 minutes to cover an area of 2–5 acres and consists of setup of the network of fixed radios. Precisely positioning the fixed radios is not required, although the units should be placed somewhat symmetrically around the survey site.

The fixed radios are numbered sequentially. Although it is arbitrary where each radio is located, it is usually beneficial to lay the units out in a sequence that is easy to remember.

After initial setup, the operator must walk a "loop" around the areas that are to be mapped. This allows the computation of relative locations of the fixed radio units. If absolute coordinates at two or more locations within the survey area are known, all relative coordinates can be rotated into geographic coordinates.

Once setup is complete, the fixed radio network needs no further attendance. The operator may begin collection.

There are no health and safety requirements for the Ranger system.

2.3 PREVIOUS TESTING OF THE TECHNOLOGY

Prior to the USACEHNC and ESTCP sponsored testing, fundamental ranging technology was tested. Because this testing was sponsored by other organizations, it is not included herein.

2.4 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The primary advantage of the Ranger approach is that a portable local area radio navigation technology allows accurate (20-50 cm) positioning in locations where other methods (primarily DGPS and laser ranging) are ineffective due to blockage from vegetation or other means. Thus, Ranger provides a geolocation technology that can be used at almost any UXO or OE remediation site.

As a stand-alone technology, Ranger is limited in positioning accuracy by the fundamental accuracy of the ranging method. Prior demonstration yielded a best-case positioning accuracy of ± 5 cm (1 σ) under optimum conditions.

In real, outdoor operating conditions, Ranger accuracy is primarily limited by multipath interference. Ranger measures the RF time-of-flight between the mobile and fixed radios. Scattered signals that bounce off trees, buildings, the ground, etc., interfere with the desired measurement. Improvement of stand-alone Ranger performance in wooded environments will primarily require improvements in multipath mitigation methods.

Ranger can operate over distances of more than 1 km in open terrain, but in heavily wooded environments, range of operation is limited to approximately 120 m.

Ranger is implemented as a two-dimensional (X, Y) positioning technology. It can be extended to three dimensions by using a network of fixed radios that are diverse in elevation or integrating an aiding altimeter.

Ranger position estimates are computed in a Kalman filter. Thus, the computational structure is designed to easily integrate other aiding sensors (such as inertial sensors, altimeters, etc.) that may improve overall system performance.

As currently implemented, one Ranger system can track the geolocation of only one mobile radio.

While Ranger fixed-location radios do not need to be accurately positioned in the field, their relative position (to each other) needs to be accurately known. Ranger position accuracies are sensitive to accuracies in relative positions of fixed radions.

Ranger is designed to be compliant with Federal Communications Commission (FCC) regulations on RF emissions, though it has not yet been submitted for approval. It is expected that Ranger could be legally operated as an unlicensed transmitting system in most of the developed world. If regulatory compliance were not a concern, positioning accuracy could be significantly increased (by increasing the operating bandwidth) and range-of-operation could be significantly increased (by increasing transmit power.)

Ranger is unaffected (within its accuracy limitations) by atmospheric conditions.

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3.0 DEMONSTRATION DESIGN

3.1 PERFORMANCE OBJECTIVES

Table 1 illustrates the overall expected objectives identified by ESTCP for the Ranger system. Many of these objectives were proven during the three ESTCP demonstrations and are presented later in Table 2.

Table 1. Ranger ESTCP Phase III Performance Objectives

Performance Criteria	Expected Performance
Unobstructed range of operation	> 1 km
Unobstructed range accuracy within range of operation	20 cm
Obstructed range of operation	500 m
Obstructed range accuracy within range of operation	20 cm
2-D position error	20 cm
Setup time	10 min
Multiple crew capability	Yes
Voice communication	Yes
Ability to capture elevation data (3-D)	Yes
Selectable accuracy	Yes
Flexible use of geophysical equipment	Yes
Real-time display of geophysical grid data	Yes
Ability to display position data in near-real-time on mobile data logger	Yes
Ability to display position data in near-real-time on remote computer	Yes
Ability to survey grids in lightly wooded areas	Yes
Ability to survey grids in moderately wooded areas	Yes
Integrated with G858	Yes
Integrated with EM61	Yes
Less than $20,000 per system cost (estimated commercial price)	Yes
Ability to determine relative position of sensor heads when coupled with geophysical instrument	Yes
Capability of the system to inform users when accuracy levels are being achieved	Yes
Capability to survey in wooded conditions with varying degrees of topography	Yes
System easy to set up and calibrate by two-person team	Yes
System easy to operate by two-person crew	Yes
Reoccupation of position easily accomplished	Yes

3.2 SELECTION OF TEST SITE

Criteria for selecting a test site are the following:

- Accessible to all project participants
- Sufficient space to accommodate the distances required for the planned tests

- Combination of open areas and areas with a variety of densities of vegetation
- Buried metallic targets that can be used to compare sensor data with and without the presence of navigation equipment
- Moderate terrain so that elevation effects will not dominate the demonstration
- A controlled site with locations of items unknown to the demonstrators so that it may be revisited to gauge improvement and compare to other technologies.

The selected test site was the APG UXO demonstration site, which met all the selection criteria. The tests conducted during this demonstration were performed in association with the ESTCP Phase III efforts of Project MM-0129.

3.3 TEST SITE/FACILITY HISTORY/CHARACTERISTICS

The Standardized UXO Sites Program uses standardized test methodologies, procedures, and facilities to help ensure that critical UXO technology performance parameters such as detection capability, false alarms, discrimination, reacquisition, and system efficiency are accurate and repeatable. The APG site is a 17-acre complex composed of five independently scored scenarios that include calibration area, blind grid, wooded, moguls, and open field. Within the open field are a variety of challenges, including electrical lines, gravel roads, fence line, wet areas, and clutter fields.

This test used the calibration, mogul and wooded areas as shown in Figure 3 through Figure 6.

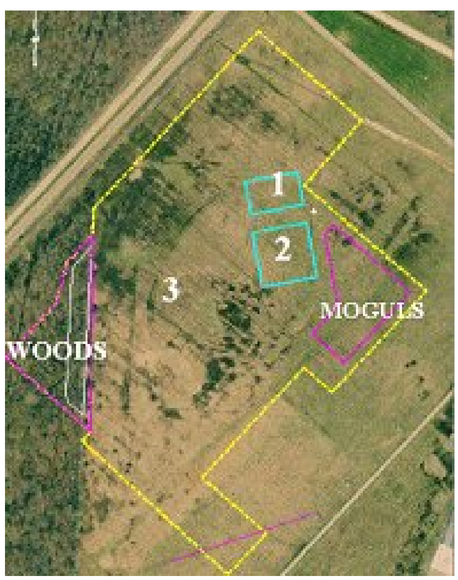

Figure 3. APG UXO Demonstration Site Layout
(1 = Calibration Area, 2 = Blind Grid, 3 = Open Field)

Figure 4. Collection of Ranger/G858 Data in Calibration Area

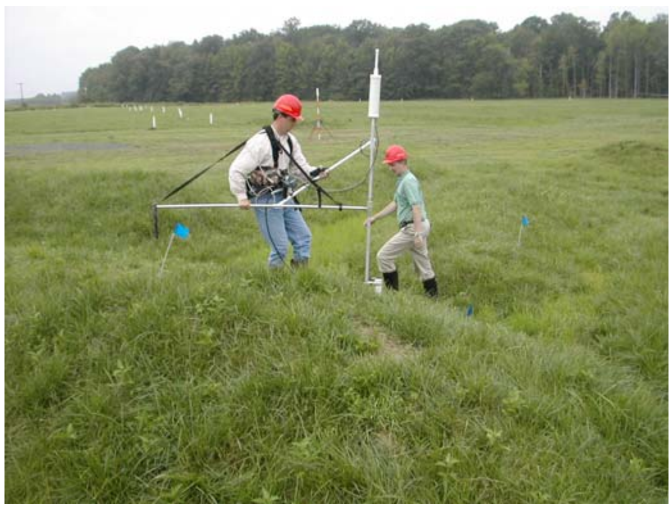

Figure 5. Collection of Ranger/G858 Data in Mogul Area

Figure 6. Collection of Ranger/G858 Data in Woods

3.4 PHYSICAL SETUP AND OPERATION

Installation of the eight fixed radios requires the following steps:

- Mount the antenna on a tripod or other mount.
- Connect the antenna to the fixed radio electronics.
- Attach a battery pack to the fixed radios.

Each step must be conducted at each radio location and requires about one minute for one person. As shown in Figure 7, at one of the fixed radios, a computer is connected to the fixed Ranger radio via a serial cable to provide real-time position display and data acquisition.

Figure 7. Ranger-Fixed Radio Setup with Laptop Connected to Perform Real-Time Data Acquisition and Display

Installation of the mobile radio requires the following steps:

- Mount the antenna on a staff.
- Connect the antenna to the mobile radio electronics.
- Connect the data logger to the mobile radio.
- Optional: Attach an EM61 or G-858 data cable to the mobile radio.
- Attach a battery pack to the mobile radio.
- Turn on the data logger.

Figure 8 shows the handheld mobile radio. Figure 9 shows the Ranger stand-alone mobile radio setup, which includes the multielement antenna mounted on a staff that is connected to the mobile radio electronics, conveniently packaged in a pouch that the operator wears on his belt. Figure 10 shows the Ranger mobile radio setup mounted on the EM61, and Figure 11 shows the Ranger mobile radio setup mounted with a G-858 magnetometer. Notice in both that the Ranger mobile radio antenna is elevated above the head of the operator to mitigate interference effects from the operator.

Figure 8. Handheld Mobile Ranger Radio

Figure 9. Stand-Alone Ranger Mobile Radio Setup

Figure 10. Ranger Mobile Radio Setup Mounted on EM61

Figure 11. Ranger Mobile Radio Setup Mounted with a G-858

The operator makes the choice of the locations of the fixed radios. Precisely positioning the fixed radios is not required. To optimize constraints on computed locations, placing the units symmetrically around the survey site is optimum.

The system must be calibrated to establish a local area coordinate system. For this demonstration, the coordinates were surveyed using a total station to ensure optimum accuracy in order to mitigate the influence of errors from the fixed stations and thus limit the errors to those contributed by the range measurements. However, although it is less accurate, operationally it is sometimes more practical to use the Ranger system solely to establish the local coordinate frame.

This can be accomplished in the following manner:

- The user must walk a circle while carrying the mobile radio that inscribes the area defined by the fixed radios.
- An iterative least-squares inversion routine then solves for both the fixed radio and mobile radio coordinates in a relative frame: Fixed unit #1 defines the origin of the coordinate system; fixed unit #2 is defined to be located at Y=0; all other fixed unit locations are fully computed.

The Ranger equipment is water-resistant but not waterproof.

As previously stated, Ranger operates in the 2.4 GHz ISM band. Once instructed by software to begin data acquisition, data collection is continuous until instructed to terminate. Operation is by a single operator in possession of the mobile Ranger radio. There is no manual interaction with the fixed radios, except at the one fixed radio where optionally a computer can be connected via serial cable to the fixed Ranger radio to log and display data. No other labor is required to operate the system.

For integrating data collected with the Ranger system with other surveys or field operations that may or may not use Ranger, the local area coordinate system must be registered to something reproducible. While Ranger operates in a 2-D mode (assumes a relatively flat or constant slope terrain), producing X and Y coordinates only, this requires having two registration points. Typically, points are registered in one of two ways—either the registration points are surveyed accurately with GPS or by some other means, or the registration points can be arbitrary points in the survey area (maybe a big rock or fire hydrant) that future surveys can use to transform one coordinate frame into another by relocating these points with the positioning system used in the future survey. To allow error analysis of coordinate translation, we recommend that at least one additional registration point be acquired.

3.5 ANALYTICAL PROCEDURES

This project is primarily focused on assessing the capabilities of Ranger in terms of location accuracy and precision.

Data analysis for Ranger includes a suite of three algorithms:

1. **Kalman Filter:** Ranger simply makes range measurements from the mobile radio to each of the fixed transponders sequentially. Each range measurement is then passed to a Kalman filter routine. The Kalman filter is a computationally efficient recursive algorithm that produces an optimal estimate of the state of a system (in this case, the position and velocity of the mobile radio). Since multipath errors are unpredictable, we have excluded range measurements in the algorithm logic when the difference between the measurement and the Kalman filter's predicted range exceeds a threshold.

2. **Kalman Smoother:** The Kalman smoother is a noncausal filter (it uses future data to make current estimates) that produces a weighted average of the forward and backward Kalman filter states. Forward Kalman filter results of states and their associated covariance matrices are stored during the real-time processing. Then, the measured ranges are passed through the Kalman filter again in reverse-time order, and the resulting states and their associated covariance matrices are stored.

3. **Median/Mean Filter:** Since the errors associated with the range measurements skew the coordinates and we obtain position estimates at a fairly high output rate of roughly 30 position estimates per second, the Kalman smoothed coordinates can be passed through a median/mean filter to further mitigate these errors (probably mostly due to multipath effects). We perform a median filter on both the x-and y-coordinate values by replacing the current coordinate value with the median value of the coordinate in a user-defined window centered on the current measurement. This is followed by a mean filter that replaces the current range coordinate with the mean value of the coordinates in a user-defined window centered on the current measurement.

The position outputs from this suite of algorithms are then ready to be interpreted.

For this demonstration, we evaluate the accuracy of the Ranger system by itself or integrated with a Geometrics G-858, depending on the acquisition scenario:

- **Positions based solely on** Ranger**:** Data acquisition consisted of an operator walking across the fixed test locations with the Ranger/G-858 system and then crossing back over those points at a 90° angle relative to the first crossing, forming an intersection where the paths crossed. We then compare the estimate of the intersection of the two Ranger paths with the true (surveyed) location of the crossover point.

- **Positions based on anomalies in G-858 data:** Data acquisition consisted of an operator walking across fixed ferrous test locations with the Ranger/G-858 system. The locations of the ferrous anomalies at each test location is estimated from the magnetic profile data and compared to the true (surveyed) location of the test object.

- **Positions based on anomalies in DGM:** Data acquisition consisted of an operator collecting data by walking a grid pattern with the Ranger/G-858 system. In this case, we assign coordinates to sensor data as above and then generate a contour map of the magnetic data. Anomaly locations are then interpreted (picked) from the map and the coordinates are compared to ground truth.

4.0 PERFORMANCE ASSESSMENT

4.1 PERFORMANCE DATA

Table 2 compares the performance objectives shown in Table 1 with the demonstrated performance of Ranger during ESTCP Phase III.

Table 2. Self-Evaluation of Performance Objectives Comparison for Ranger

Performance Criteria	Expected Performance	Demonstrated Performance
Unobstructed range of operation	> 1 km	Previously demonstrated
Unobstructed range accuracy within range of operation	20 cm	Yes
Obstructed range of operation	500 m	> 120 m
Obstructed range accuracy within range of operation	20 cm	No
2-D Position error	20 cm	20-57 cm*
Setup time	10 min	30 min
Multiple crew capability	Yes	No
Voice communication	Yes	No
Ability to capture elevation data (3-D)	Yes	No
Selectable accuracy	Yes	Yes
Flexible use of geophysical equipment	Yes	Yes
Real-time display of geophysical grid data	Yes	Yes
Ability to display position data in near-real-time on mobile data logger	Yes	Yes
Ability to display position data in near-real-time on remote computer	Yes	Yes
Ability to survey grids in lightly wooded areas	Yes	Yes
Ability to survey grids in moderately wooded areas	Yes	Yes
Integrated with G858	Yes	Yes
Integrated with EM61	Yes	Previously demonstrated
Less than $20,000 per system cost (estimated commercial price)	Yes	Yes - estimated
Ability to determine relative position of sensor heads when coupled with geophysical instrument	Yes	No
Capability of the system to inform users when accuracy levels are being achieved	Yes	No
Capability to survey in wooded conditions with varying degrees of topography	Yes	Yes
System easy to set up and calibrate by two-person team	Yes	Yes
System easy to operate by two-person crew	Yes	Yes
Reoccupation of position easily accomplished	Yes	Yes

*The conditions ranged from unobstructed, flat calibration lanes to the moderately wooded site, with errors ranging from 20 cm to 57 cm in those sites, respectively. This accuracy was achieved by surveying all fixed radio sites, respectively and by surveying all fixed radio antennas using a commercial total station surveying system.

Ranger met the project object of 20 cm in the Calibration Lanes area with a mean 2-D error of 20 cm but failed to meet the objective in the wooded site with a mean 2-D error of 57 cm.

Although voice communications were not demonstrated (nor attempted), the system supports a "pass-through" data channel that will easily support the addition of digital vocoder-based communications equipment. Multicrew (multiple mobile units) were not demonstrated and, although the system currently has not been tested with more than one mobile, firmware is in place to support up to eight simultaneous rover (mobile) units. A plan is in place to add "Z" (altitude) capabilities to the system using commercial parts to provide a full 3-D capability.

The primary sources of errors in reported coordinates for Ranger from these demonstrations include, in order of significance:

- **Multipath propagation effects:** Although there were many sources of errors in the reported coordinates, the trend toward higher errors in more cluttered environments was primarily attributed to multipath propagation effects.

- **Inability of the operator to walk accurately over the test points:** Since multipath from stationary sources is spatially dependent on the location of the mobile antenna, keeping the mobile antenna in motion as it passes over the test points enables the acquisition of range measurements that have different multipath contributions. Increased accuracy can be obtained by passing computed coordinates through a suite of smoothing filters, consisting of a median followed by a mean filter. However, the mobile antenna is held by the operator, making it difficult to accurately pass the mobile antenna over test points while walking. The tilt of the antenna can easily bias the coordinates by as much as 10-20 cm.

4.2 PERFORMANCE CRITERIA

The main objective for this demonstration was showing that Ranger was practical for use in the field for UXO and OE remediation activities. The criterion in Table 2 are simply posed as binary criteria that either exist (labeled 'Yes' in performance comparison tables) or do not exist (labeled 'No' in performance comparison tables). The primary quantitative criterion demonstrated in the series of tests was the 2-D position error in conditions ranging from the unobstructed, flat Calibration Lanes to the moderately wooded site, with errors ranging from 20 cm to 57 cm in those sites, respectively. This accuracy was achieved by surveying all fixed radio antennas using a commercial total station surveying system. Accuracy will degrade when the Ranger system is used to "self locate" the fixed radios, as described in Section 3.4, Physical Set up and Operation. The primary quantitative criterion demonstrated in the series of tests was the 2-D position error in conditions ranging from the unobstructed, flat Calibration Lanes to the moderately wooded site, with errors ranging from 20 cm to 57 cm in those sites, respectively. These errors were based on the assumption that we had survey information for the fixed radios. When survey information is unavailable, a self-location routine can be run to estimate the fixed radio locations. Based on self-located fixed radios, an average error of 34 cm (versus 20 cm) in the mobile radio location is obtained for the tests in the Calibration Lanes. Inadequate ground truth information is available to estimate mobile radio location errors in the wooded site.

4.3 DATA ASSESSMENT

Most of the criteria stated in the performance objectives are simply binary objectives since they either exist or do not exist. The quantitative criterion that required analysis was the 2-D position error, which is defined as mean value of the square root of the sum of the squares of the errors in position on the northing and easting axes for all of the points in a given test. Errors on the northing and easting axes were evaluated by differencing the computed coordinates from the ground truth coordinates generated through a conventional laser survey.

Ideally, this position error would be attributable only to errors in the positioning sensor data (due to multipath, system resolution, etc.) However, the operator's inability to walk accurately over the test points and his inability to keep the geophysical sensor level relative to the horizontal plane also contribute to the error budget. This component of the error was minimized by carefully walking over the test points and holding the sensor staff as level as possible.

4.3.1 Commercial Remediation Trial

Ranger was deployed by ARMGroup, Inc., a commercial DGM firm, for use at a live site project at Fort Devens, Massachusetts, in June 2005. Several inadequacies, mostly software, training, and operator use and expectations were identified during the trial period. Some issues were resolved on site, while some were identified as needing further development during commercialization.

Two training sessions were conducted by ENSCO, Inc. for ARMGroup personnel prior to deployment. The first session was 2 days in Hershey, Pennsylvania, at a park near the ARMGroup corporate facility. Training involved equipment setup, calibration, self-location of fixed radios, position data quality verification, geophysical survey operations, position postprocessing, and anomaly relocation. A sloping field (approximately 1.5 acres) with mainly clear line-of-site was first used so that a laser-based robotic total station (RTS) could be used to verify the accuracy of Ranger position data. Also, a thickly wooded area (approximately 1 acre) was used to train for more typical operations and to help operators understand the difference in use and accuracy in this more representative environment.

Training was performed with Ranger integrated with a Geonics EM-61. Results from the training in Hershey, PA, showed that the integrated position accuracy was between 0.3 m (field) and 0.9 m (thick woods) as reported by ARMGroup, adequate for use in their intended commercial project.

The second session was a 1-day training session conducted on site at Fort Devens, MA with ENSCO primarily observing ARMGroup. One site was set up on a heavily sloped hillside in moderately dense forest. Data quality seemed to be fine when checked after calibration of the fixed radio locations.

ARMGroup used Ranger, without assistance from ENSCO, to survey several locations within Fort Devens during a 2-week period. These locations were all in wooded hilly areas. During the collection period, several issues, mainly involving firmware failure within the Ranger system, were discovered and corrected by ENSCO. For the rest of the collections, the Ranger system

appeared to operate correctly although ARMGroup could not seem to make Ranger operate for larger than about a 60-m square grid. ENSCO has not yet determined the cause of this spatial limit; Ranger has operated with far greater distance achieved on sites in the woods.

After the 2-week collection, data were postprocessed and dig maps created from the post-analysis. Ranger was once again set up on the previously surveyed locations for reacquisition of anomalies reported in the dig maps. During reacquisition, ARMGroup found anomalies that were sometimes positioned 6 m from their actual location. ENSCO analyzed the data and found that the calibration loops ARMGroup collected to self-locate the fixed radios did not inscribe a large enough circle within the grid to give accurate positions. These errors were compounded when a different Ranger setup was employed for reacquisition. ARMGroup determined that 2 weeks of data collection were not usable and had to recollect all sites using fiducial grids.

ARMGroup assessed the productivity and data acquisition cost of Ranger as compared to RTS and fiducial survey assuming that it had operated properly. ARMGroup's reported cost assessment is shown in Table 3. ENSCO cannot validate these estimates independently.

Table 3. ARMGroup Report on Productivity and Cost

Position Method	Productivity (Acres/Day)	Cost per day	Cost per Acre
Ranger	1.25	$1,981	$1,585
RTS	1.0	$2,471	$2,471
Fiducials	1.5	$1,793	$1,195

Their further assessment was broken into positives and negatives, as shown in Table 4.

Table 4. ARMGroup Observations

Positive	Negative
Does not require line-of-site	Range appeared to be < 60 m
Provides submeter accuracy in the woods	Poor electrical connections
Easy to set up and operate	Rover malfunctions
Provides dense positioning sample rate	Insufficient real-time quality feedback
One-person operation	No ability to null the EM61 sensor
	Not rugged; cables, personal digital assistant (PDA) not protected
	Occasional programming requires extensive training or a great deal of basic knowledge
	Only one Rover is detrimental to productivity
	Difficult to integrate with different types of sensors

Finally, ARMGroup provided valuable feedback on issues that they feel need to be addressed before Ranger is useful in a full production environment.

- Self-location functionality needs to be more reliable, with better feedback on the quality of the calibration data collected.

- Connectors need to be improved.
- Real-time feedback of position data quality needs to be provided to the operator.
- If sensor data is to be collected by Ranger, nulling capability needs to be added for the EM61.
- More trial and testing with a partner company experienced in production geophysics.
- Packing and shipping needs to be more robust for daily use in the field.
- Standard operating procedures (SOP) need to clarify operations expectations

4.4 TECHNOLOGY COMPARISON

Candidate innovative alternatives to Ranger can compare well in totally unobstructed environments. However, the previously demonstrated range (distance) of operation in unobstructed environments can only be compared to differential GPS. Other technologies, such as acoustic or multiple laser tracking systems are limited in both range of operation and accuracy in wooded environments. Viable innovative alternatives have not been shown to compete within obstructed areas such as woods or hills. We have not conducted a quantitative comparison of alternative technologies.

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5.0 COST ASSESSMENT

5.1 COST REPORTING

It is anticipated that the technology resulting from this demonstration will be available either to purchase or lease. In addition to capital purchase or lease costs, associated costs include:

- Labor for mobilization and setup
- Labor for operations
- Labor for demobilization
- Maintenance (mainly battery replacement) and software upgrade.

ENSCO is working to obtain one or more licensees for the Ranger technology. We are in discussions with both equipment vendors (who would provide systems for sale) and service providers (who would provide the technology as a service). Both categories of prospective licensees are evaluating the market potential for the technology. We expect license agreements to be finalized in 2006.

While these license discussions for Ranger are ongoing, ENSCO will sell systems and support the technology. In addition, as a result of this demonstration, CEHNC has a complete Ranger system they can provide to any project as government-furnished equipment (GFE).

5.2 COST ANALYSIS

The Ranger system is a handmade, one-of-a-kind system. The cost to duplicate and deliver a copy of the current system is approximately $80,000. We anticipate that in low commercial quantities, the system will be available for purchase at approximately $25,000 – $50,000. In larger commercial quantities, system prices could approach $10,000 – $20,000.

It may be more cost-effective for contracting firms to provide Ranger as a service. Costs for this service will depend on the cost structure of the service provider and terms of the license agreement, which are not yet determined.

Ranger's demonstrated wide-area operating range (>25 acres in one setup) significantly reduces cost as compared to much shorter range ultrasonic systems. Providing large areas for survey in a single setup substantially reduces mobilization and demobilization time and cost due to the reduced manpower requirements.

5.2.1 Cost Basis

Cost of the Ranger system will be based on purchase price or cost of provision of the technology as a service. Digital geophysical maps will be a product of the daily operation, so no additional integration, mapping, or postprocessing would be required.

Data acquisition productivity with Ranger is primarily determined by the geophysical sensor being deployed. Ranger is fairly efficient to setup and requires little interaction during acquisition.

5.2.2 Cost Drivers

Cost of use of the Ranger system includes system cost and labor cost. A single operator can easily operate Ranger, though health and safety concerns and more efficient operations indicate a two-person field team is desired. Post-processing is straightforward and can be accomplished in the field.

5.2.3 Life-Cycle Costs

Life-cycle costs include acquisition, operations, and maintenance. No other costs are incurred. Batteries are rechargeable.

5.3 COST COMPARISON

Cost comparison with other potential competing technologies is difficult for several reasons. Other commercial technologies simply do not work well in the wooded environment. When compared to simple fiducial surveys, one could make the argument that there is very little setup time as compared to Ranger. However, the consistent accuracy of the Ranger system as compared to the inherent inconsistency as well as lower overall position accuracy clearly shows that Ranger will provide much better spatial geophysical data for DGM. RTS compares well in open areas but has very limited use and requires at least two operators to perform the survey.

6.0 IMPLEMENTATION ISSUES AND LESSONS LEARNED

6.1 COST OBSERVATIONS

The cost of DGM can be reduced further by commercialization of the Ranger system. Several factors were observed when Ranger was used in a commercial environment—all of which resulted from using a prototype system in the field. Some improvement was achieved during the commercial use through lessons learned, operator inexperience, training issues, and better immediate verification of data quality. The system cost will be reduced significantly through commercially "hardening" the system, as well as through greater quantity needs.

6.2 PERFORMANCE OBSERVATIONS

During the course of three demonstrations, the Ranger technology has proven to be a one-of-a-kind system, with no overall competing technology.

6.3 SCALE-UP

Cost versus quantity has been discussed previously. Full-scale implementation will provide a robust, fieldable, lightweight system, easily shipped, set up, and maintained.

6.4 OTHER SIGNIFICANT OBSERVATIONS

Users must be properly trained both in the setup and operation, as well as in expected performance. As this system is in a preproduction state, users must periodically evaluate their data for quality. Laser-based positioning systems will fail when faced with obstruction. Although Ranger will not fail in varying environments, geolocation data quality (primarily position accuracy) will vary, as with any RF-based system, due to multipath interference and certain types of obstructions. Ranger technology has the potential to provide adequate geophysical data for a wide range of site conditions, resulting in less work to be done in the field. However, the shift in required skill set must be taken into consideration. For example, even though the survey itself may require less time than with other methods, skills are currently required on site to periodically verify geolocation data quality and recommend setup solutions in particularly difficult environments.

6.5 LESSONS LEARNED

Lessons learned are described in previous sections. From the lessons learned, ENSCO has identified several improvements that would lead to successful commercialization of Ranger. Each improvement is described in the following sections.

6.5.1 Connectors and Cables

Several connectors and cables interface components within the Ranger system. Needed is a retrofit to the existing system, using connectors that are better suited to field use as well as cables that are better lengths for identified applications. Specifically, the antenna connector on the fixed radio should be replaced with a larger, more durable, weather-resistant connector that will either snap on or connect with a quarter turn. The antenna connector on the mobile radio is less

prone to environmental and physical damage; however, it would be desirable to replace both the antenna and antenna controller cable with a single cable and connector on each end.

6.5.2 Multiple Mobile Users

The current Ranger system was designed to handle up to eight mobile users simultaneously. The firmware within the mobile radio has the necessary software "hooks" to provide this; however, the software was never implemented.

6.5.3 Mobile Antenna Phased Array Design

The current mobile antenna is quite bulky and tends to weigh down the overall sensor system. It is composed of commercial off-the-shelf components, packaged for use by the Ranger system. Proposed is a low-risk custom solution that will reduce the cost, size, and weight of the current antenna subsystem and allow for the integration of Inertial Measurement Unit (IMU) and tilt compensation within a substantially smaller package. Also, the multipath performance can be enhanced by a more steerable focused antenna.

6.5.4 Fixed Radio Antenna Size Reduction

The fixed radio antennas can be replaced with smaller, high-performance directional patch antennas. This will reduce the cost and provide a more fieldable system that is also easier to ship.

6.5.5 Fixed Radio Antenna Tripod Design

A custom tripod design and delivery is needed to reduce the cost, size, and weight of each fixed radio antenna subsystem. This will allow for easier storage and shipment as well as enabling the field worker to carry more and set up more quickly.

6.5.6 Self-Location Quality Factors

Placing software within the postprocessing of self-location data is proposed. Indication would be given to the analyst as to the relative position accuracy given the loop walked during collection. Combining this with more stringent requirements for performing the bias loop (i.e. requiring the walker to circle at least two fixed radios that are furthest from each other) will assure the best results possible for the given placement of radios. Also, the self-location software would enable the user to enter surveyed locations for certain fixed radios. This information would be used in the location determination and bias calibration process. In the case where two or more fixed radios are surveyed, the information would be immediately used for real-world coordinate transformation.

6.5.7 Real-Time Data/Position Quality Indication (Audio)

It is desired to have some audio and visual indication of data quality in the field in real time. Modifications to the existing iPAQ firmware could indicate when a certain number of fixed radios are not measuring for a certain amount of time or when the signal level falls below a predefined level on some or all fixed radios. In addition to giving audible and visual information

about the quality of the raw range information, statistical information based on real-time position data quality could be indicated. The user could then assign thresholds for unacceptable position error and use this information to determine whether the data is currently acceptable. This would also assist the user in rearranging fixed radio units or adding units if needed. It would also help to maximize the area that can be covered (given the specific environment) with each system setup.

6.5.8 GGA Output and Alignment

From experience, it seems best to report a National Marine Electronics Association (NMEA) quasi-GGA string to the sensor equipment for postprocess synchronization of sensor data with position data. This would allow Ranger to be used for any sensor application that accepts a GPS input. This string would not contain precise position information, rather a time marker used during postprocessing to align the high-resolution position data with the sensor data. ENSCO has discussed this at length with Geonics and understands the implications regarding the EM-61 family of sensors. ENSCO has also briefly discussed this with G-Tek and understands how it would interface with the TM-5 Emu as well as the TM-6 sensors.

Postprocessing software would be developed to use the parsed sensor output and align the sensor data (using the GGA messages) with the position data. This would then be output to a file in a suitable format for geophysical analysis.

6.5.9 Cavity Filter Removal

A significant cost to the Ranger system is the cavity filter that is used in the fixed radio units. A plan is in place to remove the filters and replace them with small, less expensive ceramic filters. This will make the fixed radio much less expensive and also reduce the size and weight, making field setup easier.

6.5.10 Crystal Clock Oscillator Replacement

A recent modification was performed to increase the range measurement stability over a wide temperature range. The clock oscillators that are used turned out to be rather fragile, and the modification placed them in danger of physical breakage whenever the fixed or mobile radio is bumped against a hard surface. The problem has been fully characterized and a solution has been developed.

6.5.11 Mobile Antenna/IMU Integration (Tilt)

Sensor tilt is a source of large error when using any antenna that is 4 to 6 ft above the center of the sensor, especially when traversing hills or going over obstacles such as rocks or logs. The integration of IMU/tilt capabilities will serve two purposes. First, it will aid the Ranger position information, greatly increasing accuracy when dropouts and multipath are present, and second, it will give the postprocessing software the information it needs to perform tilt correction to the position.

6.5.12 1-PPS Output

GPS units output a pulse (usually time to live [TTL] level) at a rate of 1/sec. This is used to precisely (<1 µs error) demark the offset of the following time message within the GGA string. This could be used similarly to reduce the potential serial port latency when storing the GGA message provided by Ranger. A multiple of this pulse could also be used to trigger a sensor precisely with respect to the Ranger position data. As far as ENSCO can find out, only the G-Tek TM-5 Emu and the TM-6 sensors currently take advantage of this signal. It would be very straightforward to apply a multiple (say 10 or 15 times per second) to the trigger input on the Geonics EM-61 sensors.

Further, a small hardware interface to the 1-pulse per second (PPS) development would provide output at various voltage levels, as well as programmable multiple frequency output synchronized to the primary 1PPS output.

6.5.13 GPS on Fixed Radio Antennas

The addition of a relatively inexpensive GPS unit on each of the fixed radio antenna subsystems will greatly enhance the self-location capabilities. All units (that have GPS coverage) would converge over time to a very good position relative to all other GPS units. While the Ranger system is primarily used in areas that are wooded or otherwise do not have GPS available, it is not unreasonable to expect that several fixed radios may have good GPS availability. This information would be used in postprocessing to increase the accuracy of self-location results as well as to adjust the range bias values. This involves either the integration with the fixed radio electronics for transmission of GPS information to the mobile unit(s) or local data logging for subsequent GPS data download and processing.

6.5.14 X-Scale Integration with Mobile Radio (Eliminate iPAQ)

Embedding a processor in the mobile radio unit allows for stand-alone operation (without an external PDA) and would implement the real-time Kalman filter, generating position information for use in relocation activities. X-Scale is proposed because it will allow for relatively easy upgrade to the firmware using either Linux or WinCE operating system.

The embedded real-time Kalman filter would also allow reduced accuracy position (as compared to postprocessed position) for use in applications that require real-time navigation and position. ENSCO has successfully embedded the Kalman filter within the iPAQ for reoccupation use; this code may be ported to the X-Scale embedded processor. The real-time position information would be output in the NMEA strings.

6.6 END-USER ISSUES

Several approaches are available to end users who want to implement Ranger technology. Consideration has been given to licensing the technology and has been discussed in previous sections.

6.7 APPROACH TO REGULATORY COMPLIANCE AND ACCEPTANCE

Ranger technology utilizes commercial 802.11b wireless local area network (LAN) components as the main transmission method. As such, the Ranger system is inherently FCC-+compliant in the U.S. and most other countries and operates within the unlicensed ISM bandwidth. The actual hardware used has not been certified by the FCC. In recent years, this process has become quite streamlined, and requires approximately 1–2 months to complete the government approval process.

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APPENDIX A

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